

Nonthermal emission model of isolated X-ray pulsar RX J0420.0-5022

N. Chkheidze¹, Iu. Babyk^{2,3,4}

¹Center for theoretical Astrophysics, ITP, Ilia State University, 0162, Tbilisi, Georgia

²Main Astronomical Observatory of NAS of Ukraine, Zabolotnogo str., 27, 03680, Kyiv, Ukraine

³Dublin Institute for Advanced Studies, Fitzwilliam Place., 31, Dublin 2, Ireland

⁴Dublin City University, Dublin 9, Ireland

nino.chkheidze@iliauni.edu.ge, babikyura@gmail.com

In the present paper an alternative theoretical interpretation to the generally assumed thermal emission models of the observed X-ray spectrum of isolated pulsar RX J0420.0-5022 is presented. It is well known that the distribution function of relativistic particles is one-dimensional at the pulsar surface. However, cyclotron instability causes an appearance of transverse momenta of relativistic electrons, which as a result, start to radiate in the synchrotron regime. On the basis of the Vlasov's kinetic equation we study the process of the quasi-linear diffusion (QLD) developed by means of the cyclotron instability. This mechanism provides generation of optical and X-ray emission on the light cylinder lengthscales. The analysis of the three archival XMM-Newton observations of RX J0420.0-5022 is performed. Considering a different approach of the synchrotron emission theory, the spectral energy distribution is obtained that is in a good agreement with the observational data. A fit to the X-ray spectrum is performed using both the present synchrotron emission model spectrum absorbed by cold interstellar matter and generally assumed absorbed black-body model.

Key words: pulsars: individual RX J0420.0-5022, stars: magnetic fields, radiation mechanisms: non-thermal

INTRODUCTION

The soft X-ray source *RXJ0420.0-5022* (hereafter RXJ0420) belongs to the group of seven radio-quiet, isolated neutron stars discovered in the ROSAT all-sky survey data and often called the X-ray Dim Isolated Neutron Stars (XDINSs, see [10] for review). In the optical domain, only a few XDINSs have counterparts certified by their proper motion measurements and likely candidates are proposed for remaining, based on their coincidence with the X-ray positions [17]. The X-ray spectra of XDINSs are well represented by an absorbed black-body ($kT \approx 45 - 100\text{eV}$) which is emitted by the hotter part of the neutron star surface [10]. Whereas, the cooler part of the XDINSs surface is assumed to be emitting in the optical domain [20]. The formation of a non-uniform distribution of the surface temperature is still under debate, which is more likely artificial and needs to be examined by convincing theory. The optical emission is also explained in terms of hydrogen layers of finely tuned thickness superposed on a condensed matter surface reprocessing the surface radiation [11], or of non-thermal emission from particles in the star magnetosphere [18].

Alternatively to somewhat contrived thermal emission models the observed properties of the faintest object in X-rays among the XDINSs RXJ0420 can be explained in the framework of the plasma emission model. This model has already been applied to explain the observed spectra of two other XDINSs (RX J1856.5-3754 and RBS1774, see [4, 5] for more details). The plasma emission model is based on the well-developed theory of pulsars [14, 15] and suggests successful interpretation of the observational data. According to these works, in the electron-positron plasma of a pulsar magnetosphere the low frequency cyclotron modes, on the quasi-linear evolution stage create conditions for generation of the high energy synchrotron emission. Generally speaking, at the pulsar surface relativistic particles efficiently lose their perpendicular momenta via synchrotron emission in very strong magnetic fields and therefore, they very rapidly transit to their ground Landau state (pitch angles are vanishing). However, the cyclotron instability causes appearance of transverse momenta of relativistic particles in the outer parts of the pulsar magnetosphere. Therefore, the resonant electrons start to radiate in the synchrotron regime.

We suppose that the observed X-ray emission of RXJ0420 is generated by the synchrotron mechanism at the light cylinder length-scales. In general the synchrotron radiation spectrum is considered to be a power-law, which is not consistent with the observational data from RXJ0420. The standard theory of the synchrotron radiation [2, 7] typically provides the power-law spectral energy distribution. Contrary to the

standard scenario, by taking into account the specifications produced due to the present emission model we obtain different spectral distribution, which can be successfully fitted with the measured X-ray spectrum of RXJ0420.

In the present paper, we describe the plasma emission model and derive the synchrotron radiation spectrum based on our scenario (Sec. 2), present the results of spectral analysis of re-processed XMM-Newton archival data from RXJ0420 (Sec.3), and make conclusions (Sec. 4).

EMISSION MODEL

Any well known theory of pulsar emission suggests that, the observed radiation is generated due to processes taking place in an electron-positron plasma. It is generally assumed that the pulsar magnetosphere is filled by dense relativistic electron-positron plasma with an anisotropic one-dimensional distribution function (see Fig. 1 from [1]) and consists of the following components: a bulk of plasma with an average Lorentz-factor $\gamma_p \simeq 10^2$, a tail on the distribution function with $\gamma_t \simeq 10^5$, and the primary beam with $\gamma_b \simeq 10^7$. The distribution function is one-dimensional and anisotropic and plasma becomes unstable, which might cause excitation of the plasma eigen modes. While considering the eigen-modes of the electron-positron plasma having small inclination angles with respect to the magnetic field, one has three branches, two of which are mixed longitudinal-transversal waves ($lt_{1,2}$). The high frequency branch on the diagram $\omega(k_{\parallel})$ begins with the Langmuir frequency and for longitudinal waves ($k_{\perp} = 0$), lt_1 reduces to the pure longitudinal Langmuir mode. The low frequency branch, lt_2 , is similar to the Alfvén wave. The third t mode, is the pure transversal wave, the electric component of which \mathbf{E}^t is perpendicular to the plane of the wave vector, and the magnetic field, $(\mathbf{k}, \mathbf{B}_0)$. The vector of the electric field, \mathbf{E}^{lt_1, lt_2} is located in the plane $(\mathbf{k}, \mathbf{B}_0)$. When $k_{\perp} = 0$, the t -mode merges with the lt waves and the corresponding spectra is given by [12]

$$\omega_t \approx kc(1 - \delta), \quad \delta = \frac{\omega_p^2}{4\omega_B^2\gamma_p^3} \quad (1)$$

where k is the modulus of the wave vector, c is the speed of light, $\omega_p \equiv \sqrt{4\pi n_p e^2/m}$ is the plasma frequency, e and m are the electron's charge and the rest mass, respectively, n_p is the plasma density, $\omega_B \equiv eB/mc$ is the cyclotron frequency and B is the magnetic field induction.

The main mechanism of wave generation in plasmas of the pulsar magnetosphere is the cyclotron instability. The cyclotron resonance condition can be written as [12]:

$$\omega - k_{\parallel}V_{\parallel} - k_x u_x + \frac{\omega_B}{\gamma_r} = 0, \quad (2)$$

where $u_x = cV_{\varphi}\gamma_r/\rho\omega_B$ is the drift velocity of the particles due to curvature of the field lines with the curvature radius ρ . During the wave generation process, one also has a simultaneous feedback of these waves on the resonant electrons [24]. This mechanism is described by the QLD, leading to a diffusion of particles as along as across the magnetic field lines. Therefore, resonant particles acquire transverse momenta (pitch angles) and, as a result, start to radiate through the synchrotron mechanism.

The wave excitation leads to redistribution process of the resonant particles via the QLD. The kinetic equation for the distribution function of the resonant electrons can be written as [4]:

$$\begin{aligned} \frac{\partial f^0}{\partial t} + \frac{\partial}{\partial p_{\parallel}} \{F_{\parallel} f^0\} + \frac{1}{p_{\perp}} \frac{\partial}{\partial p_{\perp}} \{p_{\perp} F_{\perp} f^0\} = \\ = \frac{1}{p_{\perp}} \frac{\partial}{\partial p_{\perp}} \left\{ p_{\perp} D_{\perp, \perp} \frac{\partial}{\partial p_{\perp}} f^0(\mathbf{p}) \right\}. \end{aligned} \quad (3)$$

where

$$F_{\perp} = -\alpha_s \frac{p_{\perp}}{p_{\parallel}} \left(1 + \frac{p_{\perp}^2}{m^2 c^2} \right), \quad F_{\parallel} = -\frac{\alpha_s}{m^2 c^2} p_{\perp}^2, \quad (4)$$

are the transversal and longitudinal components of the synchrotron radiation reaction force and $\alpha_s = 2e^2\omega_B^2/3c^2$.

Here $D_{\perp,\perp}$ is the perpendicular diffusion coefficient, which can be defined as follows [4]

$$D_{\perp,\perp} = \frac{e^2}{8c} \delta |E_k|^2, \quad (5)$$

where $|E_k|^2$ is a density of electric energy in the waves and its value can be estimated from the expression $|E_k|^2 \approx mc^2 n_b \gamma_b c / 2\omega$, where ω is the frequency of the cyclotron waves.

The transversal QLD increases the pitch-angle, whereas force F_{\perp} resists this process, leading to a stationary state ($\partial f / \partial t = 0$). The pitch-angles acquired by resonant electrons during the process of the QLD satisfies $\psi = p_{\perp} / p_{\parallel} \ll 1$. Thus, one can assume that $\partial / \partial p_{\perp} \gg \partial / \partial p_{\parallel}$. In this case the solution of Eq.(3) gives the distribution function of the resonant particles by their perpendicular momenta [4]

$$f(p_{\perp}) = C \exp \left(\int \frac{F_{\perp}}{D_{\perp,\perp}} dp_{\perp} \right) = C e^{-\left(\frac{p_{\perp}}{p_{\perp 0}} \right)^4}, \quad (6)$$

where

$$p_{\perp 0} \approx \frac{\pi^{1/2}}{B \gamma_p^2} \left(\frac{3m^9 c^{11} \gamma_b^5}{32e^6 P^3} \right)^{1/4}. \quad (7)$$

And for the mean value of the pitch angle we find $\psi_0 \approx p_{\perp 0} / p_{\parallel} \simeq 10^{-3}$. Synchrotron emission is generated as the result of appearance of pitch angles.

SYNCHROTRON RADIATION SPECTRUM

To explain the observed X-ray emission of RXJ0420, let us assume that the resonant particles are the primary beam electrons with $\gamma_b \sim 10^7$, giving the synchrotron radiation in the soft X-ray domain. According to our emission scenario, the synchrotron radiation is generated as the result of acquirement of pitch angles by resonant particles, during the QLD stage of the cyclotron instability. As was shown in [16], the cyclotron resonance condition (see Eq. (2)) is fulfilled at the light cylinder lengthscales. Consequently, the observed X-ray emission comes from the region near the light cylinder, where the geometry of the field lines is determined by the curvature drift instability excited at the same lengthscales [19]. The curvature drift instability effectively rectifies the magnetic field lines (the curvature radius tends to infinity). Therefore, in the synchrotron emission generation region the field lines are practically straight and parallel to each other and one can assume that electrons with $\psi \approx \psi_0$ efficiently emit in the observer's direction.

The synchrotron emission flux of the set of electrons in this case is given by (see [4])

$$F_{\epsilon} \propto \int f_{\parallel}(p_{\parallel}) B \psi_0 \frac{\epsilon}{\epsilon_m} \left[\int_{\epsilon/\epsilon_m}^{\infty} K_{5/3}(z) dz \right] dp_{\parallel}. \quad (8)$$

Here $f_{\parallel}(p_{\parallel})$ is the distribution function of the resonant electrons by their parallel momenta, $\epsilon_m \approx 5 \cdot 10^{-12} B \psi \gamma^2 \text{keV}$ is a photon energy of maximum of the synchrotron spectrum of a single electron and $K_{5/3}(z)$ is the Macdonald function.

In order to find the synchrotron emission spectrum, one needs to know the behaviour of the distribution function, $f_{\parallel}(p_{\parallel})$. For solving this problem, we consider the equation governing the evolution of $f_{\parallel}(p_{\parallel})$ [4]

$$\frac{\partial f_{\parallel}}{\partial t} = \frac{\partial}{\partial p_{\parallel}} \left(\frac{\alpha_s}{m^2 c^2 \pi^{1/2}} p_{\perp 0}^2 f_{\parallel} \right). \quad (9)$$

Considering the quasi-stationary case from Eq. (9) we can find the redistributed distribution function of the resonant particles by their parallel momenta

$$f_{\parallel} \propto \frac{1}{p_{\parallel}^{1/2} |E_k|}. \quad (10)$$

On the other hand, the cyclotron noise is described by the equation

$$\frac{\partial |E_k|^2}{\partial t} = 2\Gamma_c |E_k|^2, \quad (11)$$

where

$$\Gamma_c = \frac{\pi^2 e^2}{k_{\parallel}} f_{\parallel}(p_r), \quad (12)$$

is the growth rate of the instability and from the resonance condition (2) it follows that $k_{\parallel} \approx \omega_B / c\delta\gamma_r$.

Combining Eqs. (9) and (11) it is easy to find that [4]:

$$|E_k|^2 \propto p_{\parallel}^{3-2n}, \quad (13)$$

here n denotes the index of the initial distribution function of the resonant electrons ($f_{\parallel 0} \propto p_{\parallel}^{-n}$). From Eqs. (10) and (13) it follows that $f_{\parallel}(p_{\parallel}) \propto p_{\parallel}^{n-2}$. As the emitting particles in our case are the primary beam electrons, nothing can be told about their initial distribution. We only know the scenario of creation of the primary beam electrons [8, 3] which are extracted from the pulsar's surface via the electric field induced due to star rotation. To our knowledge there is no convincing theory that would predict the initial form of the distribution function of the beam electrons, which must be drastically dependent on the neutron star's surface properties and temperature.

The frequency of the original waves, excited during the cyclotron resonance can be estimated from Eq. (2) as follows

$$\nu \approx 2\pi \frac{\omega_B}{\delta\gamma_b} \sim 10^{14} Hz. \quad (14)$$

As we can see the frequency of the cyclotron modes comes in the same domain as the measured optical emission of XDINSs with the certified optical counterparts. Their spectra mostly follow the the Rayleigh-Jeans tail $F_{\nu} \propto \nu^2$. On the other hand, the spectral distribution of the cyclotron modes is given by expression (13) and combining this equation with Eq. (14) we find

$$F_{\nu} \propto |E_k|^2 \propto \nu^{2n-3}. \quad (15)$$

From Eq. (15) it follows that when $n = 5/2$ the spectral distribution of the cyclotron modes is coincident with the Rayleigh-Jeans function. And for the initial distribution of the beam electrons, as for their final distribution we find $f_{\parallel 0} \propto p_{\parallel}^{-5/2}$ and $f_{\parallel} \propto p_{\parallel}^{1/2}$. We have used this distribution for the beam electrons to define the theoretical X-ray spectrum of RX J1856.5-3754, which well fitted the measured one [5]. Although, for RXJ0420 it is not yet confirmed the detection of the optical counterpart, based on the similarity of XDINSs we assume that the initial distribution function of the beam electrons must be the same for all XDINSs. Thus, in place of integral (8) as for two other XDINSs investigated in previous works [4, 5] we get:

$$F_{\epsilon} \propto \epsilon^{0.3} \cdot e^{-(\epsilon/\epsilon_m)^b}. \quad (16)$$

To find the values of the parameters b and ϵ_m , one should perform a spectral analysis by fitting the model spectrum absorbed by cold interstellar matter with the observed X-ray spectrum of RXJ0420.

SPECTRAL ANALYSIS

To obtain the X-ray spectra of RXJ0420 with the highest statistical quality we used the EPIC-pn data collected from three XMM-Newton observations between December 2002 and January 2003. The archival XMM-Newton data were processed with the Science Analysis Software (SAS) version 11.0. The X-ray spectra were grouped in spectral bins containing at least 30 photons. Subsequent spectral analysis was performed with XSPEC V12.7.0. The three EPIC-pn spectra of RXJ0420 were fit simultaneously and spectral analysis was limited to energies between 0.15 and 1.0 keV. Along with the plasma emission model proposed in the present work we also examined the black-body model, to compare the fit results.

Table 1: Model-Fit spectral parameters of RXJ0420.0-5022 for combined fits to the EPIC-pn spectra obtained from individual observations in the energy interval 0.15 – 1.0 keV.

Model	N_H (10^{20} cm^{-2})	ϵ_m (keV)	b	kT_{bb}^∞ (eV)	E_{edge} (keV)	τ_{edge}	$\chi^2(\text{dof})$
plasma	$1.00^{+0.28}_{-0.28}$	0.10 ± 0.04	1.27 ± 0.31				1.51(96)
plasma*edge	$1.00^{+0.37}_{-0.37}$	0.10 ± 0.05	1.27 ± 0.42		$0.30^{+0.01}_{-0.01}$	$0.68^{+0.30}_{-0.30}$	1.10(94)
bbbody	$1.01^{+0.19}_{-0.19}$			43.3 ± 1.2			1.47(97)
bbbody*edge	$1.01^{+0.33}_{-0.33}$			46.3 ± 1.8	$0.31^{+0.02}_{-0.02}$	$0.69^{+0.21}_{-0.21}$	1.10(95)

THE BLACK-BODY MODEL

For the spectral analysis of EPIC-pn data for RXJ0420 first we used an absorbed black-body model. We allowed only the black-body normalization to vary between the spectra of the individual observations and fitted the temperature and amount of interstellar matter as common parameters. We found that the black-body provided a reasonable fit, but with $N_H \sim 10^{18} \text{ cm}^{-2}$, that is not perfect. Thus, we set a lower limit for this parameter, which did not change drastically the fit quality. The resulting $\chi^2 = 1.47$ for 97 degrees of freedom and for the column density we got $N_H = (1.01 \pm 0.19) \times 10^{20} \text{ cm}^{-2}$. The best fit black-body temperature $kT_{bb}^\infty = 43 \text{ eV}$ appears to be the lowest value derived from any of the known XDINSs (see parameters in Table 1).

THE SYNCHROTRON EMISSION MODEL

The plasma emission model proposed in the present paper was recently applied to explain the X-ray spectra of RX J1856.5-3754 and RBS1774, revealing good fit quality in both cases [4, 5]. We performed fitting of the model spectrum (Eq.(16)) absorbed by cold interstellar matter with the EPIC-pn spectra of RXJ0420. The best fit results are $b = 1.27$ and $\epsilon_m = 0.1 \text{ keV}$, corresponding $\chi^2 = 1.51$ for 96 degrees of freedom. The column density N_H , ϵ_m and b were treated as free parameters common to all three spectra. Only normalization was allowed to vary freely for different spectra independently, as in previous case when applying the black-body model. The fit results are listed in Table 1.

DISCUSSION

The spectral analysis of the pulse phase-averaged X-ray spectra of RXJ0420 shows that the fits quality in case of both models (black-body and plasma emission models) is not very good. From inspection of Fig.1 one might consider the residuals around 0.3keV as an absorption feature. This feature, described as a broad ($\sigma = 70 \text{ eV}$) Gaussian absorption line was noted and discussed by [9]. We add the absorption line at $\sim 0.3 \text{ keV}$ to both models considered in the present work and re-fit the data. The fit quality improves in both cases, only if using an absorption edge model. The best-fitting energy of the edge is $E_{edge} \approx 0.3 \text{ keV}$, and the optical depth $\tau_{edge} \approx 0.7$ (see Tab.1). The resulting value of χ^2 reduces to 1.1 for both models.

The nature of the spectral features discovered in X-ray spectra of XDINSs is not fully clarified as yet. According to the thermal emission scenarios the most likely interpretation of the absorption lines is that they appear due to proton cyclotron resonance. The proton cyclotron absorption line at $\sim 0.3 \text{ keV}$ implies the magnetic field of $B_{cyc} = 6.6 \times 10^{13} \text{ G}$, which differs from the value of the dipolar magnetic field inferred from the timing measurements $B_{dip} = 1.0 \times 10^{13} \text{ G}$ [10].

We suppose that existence of the absorption feature in X-ray spectra of RXJ0420 might be caused by wave damping at photon energies $\sim 0.3 \text{ keV}$, which takes place near the light cylinder. During the farther motion in the pulsar magnetosphere, the X-ray emission might come in the cyclotron damping range. If we assume that damping happens on the left slope of the distribution function of primary beam electrons (see Fig. 1 from [1]), then the photon energy of damped waves will be $\epsilon_0 = (h/2\pi)2\omega_B/\gamma_b\psi^2 \simeq 0.3 \text{ keV}$ [4].

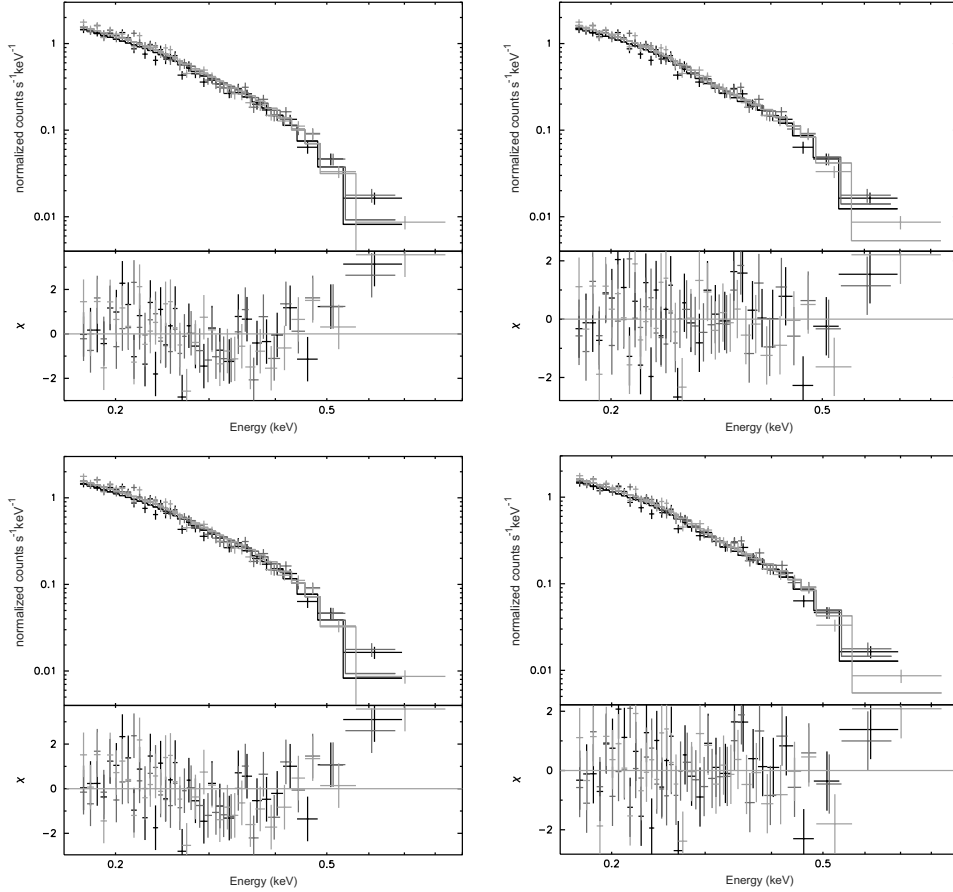


Fig. 1: Combined EPIC-pn spectra of RX J0420.0-5022. Top left: The absorbed black-body model fit. Top right: The black-body model fit including an absorption edge at $\sim 0.3\text{keV}$. Bottom left: The synchrotron emission model fit absorbed by cold interstellar matter. Bottom right: Model fit including absorption edge at 0.3keV .

Taking into account the shape of the distribution function of beam electrons, we interpret the large residuals around $\sim 0.3\text{keV}$ as an absorption edge.

Despite the fact that fit quality considerably improves when including the absorption edge at 0.3keV for both emission models, the physical reality of this feature is still uncertain. It might be caused by calibration uncertainties. A feature of possible similar nature was detected in EPIC-pn spectra of the much brighter prototypical object RXJ1856.4-3754 and classified as remaining calibration problem by [10]. Thus, we agree that more data are necessary to finally prove or disprove the existence of this feature.

According to the fit results (see Tab.1) the spectral analysis of the measured EPIC-pn X-ray spectra of RXJ0420 does not seem to be enough to distinguish between the black-body and the plasma emission models. Differently from the thermal radiation models, which appear to be somehow artificial, our scenario is based on a self-consistent theory. According to works of [21] and [22] due to the cascade processes of a pair creation the pulsar's magnetosphere is filled by electron-positron plasma with the anisotropic one-dimensional distribution function. The beam particles undergo drifting perpendicularly to the magnetic field due to the curvature, of the field lines. Both of these factors (the one-dimensionality of the distribution function and the drift of particles) might cause the generation of eigen modes in the electron-positron plasma if the condition of cyclotron resonance is fulfilled. The generated waves interact with the resonant electrons via the QLD, which leads to the diffusion of particles as along as across the magnetic field lines, and inevitably causes creation of pitch angles by resonant particles. Therefore, the resonant electrons start to radiate in the synchrotron regime.

The estimations show that for the beam electrons with the average Lorentz-factor $\gamma_b \sim 10^7$, the synchrotron radiation comes in the same domain as the measured X-ray spectrum of RXJ0420. Differently from the standard theory of the synchrotron emission [7], which only provides the power-law spectrum, our

approach gives the possibility to obtain different spectral energy distributions. In the standard theory of the synchrotron emission, it is supposed that the observed radiation is collected from a large spacial region in various parts of which, the magnetic field is oriented randomly. Thus, it is supposed that along the line of sight of an observer the magnetic field directions are chaotic. In our case the emission comes from the region of the pulsar magnetosphere where the magnetic field lines are practically straight and parallel to each other. And differently from standard approach, we take into account the mechanism of creation of the pitch angles, which inevitably restricts their possible values.

ACKNOWLEDGEMENT

The authors are grateful to Prof. George Machabeli for valuable discussions. The HEASARC online data archive at NASA/GSFC has been used extensively in this research.

REFERENCES

- [1] Arons J. 1981, in Proc. Varenna Summer School and Workshop on Plasma Astrophysics, ESA, 273
- [2] Bekefi G. & Barrett A. H. 1977, 'Electromagnetic vibrations, waves and radiation', The MIT Press, Cambridge, Massachusetts and London, England
- [3] Beskin V. S. MHD Flows in Compact Astrophysical Objects. Springer, 2010, 425 p.
- [4] Chkheidze N. 2011, A&A, 527, 2C
- [5] Chkheidze N. 2012, NewA, 17, 227C
- [6] Dyks J. & Rudak B. 2000, A&A, 326, 1004
- [7] Ginzburg V. L. 1981, 'Teoreticheskaya Fizika i Astrofizika', Nauka, Moskva
- [8] Goldreich P. & Julian W.H. 1969, ApJ, 157, 869
- [9] Haberl F. 2004, A&A, 424, 635
- [10] Haberl F. 2007, Ap&SS, 308, 181
- [11] Ho W. C. G., Kaplan D. L., Chang P., Adelsberg M., Potekhin A. Y. 2007, MNRAS 375, 281H
- [12] Kazbegi A. Z., Machabeli G. Z. & Melikidze G. I. 1992, in Proc. IAU Collog. 128, The Magnetospheric Structure and Emission Mechanisms of Radio Pulsars, ed. T.H. Hankins, J.M. Rankin & J.A. Gil (Zielona Gora: Pedagogical Univ. Press), 232
- [13] Kontorovich V. M. & Flanchik A. B. 2012, eprint arXiv:1210.2858
- [14] Lominadze J. G., Machabeli G. Z. & Usov V. V. 1983, Ap&SS, 90, 19L
- [15] Machabeli G. Z. & Usov V. V. 1979, AZh Pi'sma, 5, 445
- [16] Malov I. F., Machabeli G. Z. 2002, Astronomy Reports, 46, 8, 684
- [17] Mignani R. P., Falomo R., Moretti A., et al. 2008, A&A, 488, 267
- [18] Motch C., Zavlin V. E. & Haberl F. 2003, A&A, 408, 323
- [19] Osmanov Z., Shapakidze D., & Machbeli G. 2009, A&A, 509, 19
- [20] Pons J. A., Walter F. M., Lattimer J. M., et al. 2002, ApJ, 564, 981
- [21] Sturrock P. A. 1971, ApJ, 164, 529
- [22] Tademaru E. 1973, ApJ, 183, 625
- [23] Van Kerkwijk M. H. & Kulkarni S. R. 2001, A&A, 378, 986V
- [24] Vedenov A. A., Velikhov E. P. & Sagdeev R. Z. 1961, Soviet Physics Uspekhi, 4, 2, 332